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3D WOVEN COMPOSITES FOR NEW AND INNOVATIVE IMPACT AND PENETRATION RESISTANT SYSTEMS

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13. ABSTRACT *(Maximum 200 words)*

The objective of the Phase I study is to develop innovative high performance composites with superior ballistic damage tolerance capability suitable for armors and structures. Development of 3D triaxial weave composites, composite panels fabrication and testing have been completed. Good correlation of numerical simulation results with experimental data for ballistic velocity limits (V50) of plain weave and orthogonal weave panels has been demonstrated.

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PROGRAM ACTIVITY

WORK SUMMARY

Configuration development of 3D triaxial weave composites has been conducted. Parametric study of 3D woven composites to characterize the effect of fiber architecture on the panel ballistic performance has been performed. Composite panels have been fabricated and ballistic tests have been conducted to characterize the V-50 values for verification of the analytical procedure and material concepts. Analytical results have demonstrated good correlation of numerical simulation results with experimental data for ballistic velocity limits (V50) of plain weave and orthogonal weave panels.

STUDIES

In this reporting period work has been performed on: (1) innovative concept development per Task II, (2) panel fabrication per Task III, and (3) ballistic testing and correlation per Task IV. The activities are summarized below.

TASK I – INNOVATIVE CONCEPT DEVELOPMENT AND DESIGN

Material Concept Selection

Through a literature survey performed previously at MSC [1], two basic 3D textile forms including orthogonal interwoven weaves and 3D braids together with the MSC's "Substrate" family of 3D triaxial weaves have been selected for further evaluation of their ballistic resistance performance.

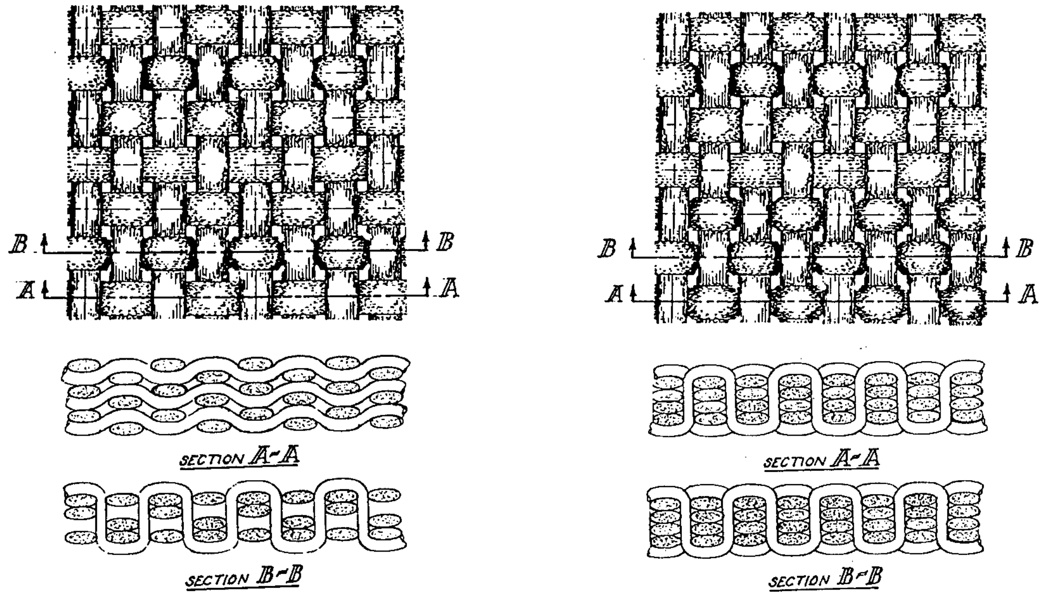
The general guideline for ballistic resistance design is that one seeks the highest possible modulus in order to spread the impact energy over a wide area via increased wave speed. In addition, it requires high strengths so that the process may be carried as far from the impact point as possible. Traditional laminated composites provide structures with satisfactory in-plane stiffness and strength, however, with a tradeoff of undesired through the thickness properties. It becomes obvious that enhanced delamination resistance can be obtained by including through the thickness reinforcements.

Orthogonal Weaves

Biaxial multi-layer constructions, such as the 3-D orthogonal or angle-interlock weaves and orthogonal weaves are commonly used but they are also known to have a high void content (regions with low fiber volume fraction). More complete close interweaving of multi-layer constructions of the 3-D orthogonal weave shown in Figure 1a can significantly reduce the void content but they are still riddled with voids. Such voids can be reduced or perhaps essentially eliminated by less interweaving of the central layers (Figure 1b) in a kind of thru-the-thickness basket weave. Such a weave obviously would become less and less inherently stable as the number of stacked intermediate warp yarns increases. However, for thin plate applications, such simple weaves may be of interest.

Triaxial Weaves

Methods for close interweaving of triaxial multilayer constructions are available. Triaxial constructions related to the "Substrate" family of triaxial weaves have been developed at MSC to achieve a low void content. The original Substrate weave was patented by Dow in 1975. The basic qualities of the Substrate weave are its multidirectional reinforcement within a single ply (lead to improved in-plane shear and delamination properties) and high fiber volume fractions (maximizing the elastic properties and strength for this configuration). MSC has expanded on this original design to allow multilayer constructions, (for higher load intensity applications), which have through the thickness reinforcement (for improving strength and damage tolerance). Shown in Figure 2 is a 3D triaxial with 0/±60 warp yarn angles. Through the thickness running yarns (0° warp) are provided in addition to the in-plane triaxial construction. The triaxial weave shown in Figure 2 has been selected for ballistic evaluation in this Phase I study. Further implementation of the Substrate families will be conducted in Phase II.



(a) (b)

Figure 1. 3D Multi-Layer Orthogonal Interwoven Constructions (a) More Completely Interwoven Construction, but Still Create Voids or Resin-Rich Regions, (b) Possible Tightly Packed Biaxial Multi-Layer Weave

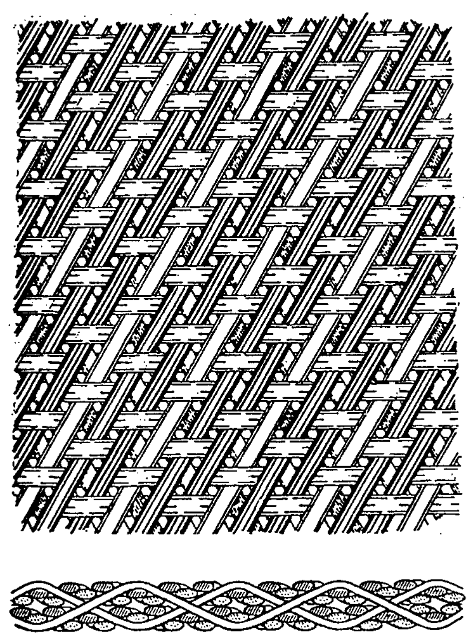


Figure 2. Multi-Layer Triaxial ("Substrate") Weave, the Cross Section Plot Shows a Two-Layer Construction, Which can be Extended to Multi-Layers

3D Braided Weaves

3D braided composites utilizing 2-step and 4-step techniques have been well developed. Their base geometric configurations have been well documented by textile researchers, e.g., [2,3]. The 3D 4-step braided composite has been selected for comparison.

Ballistic Impact Analysis

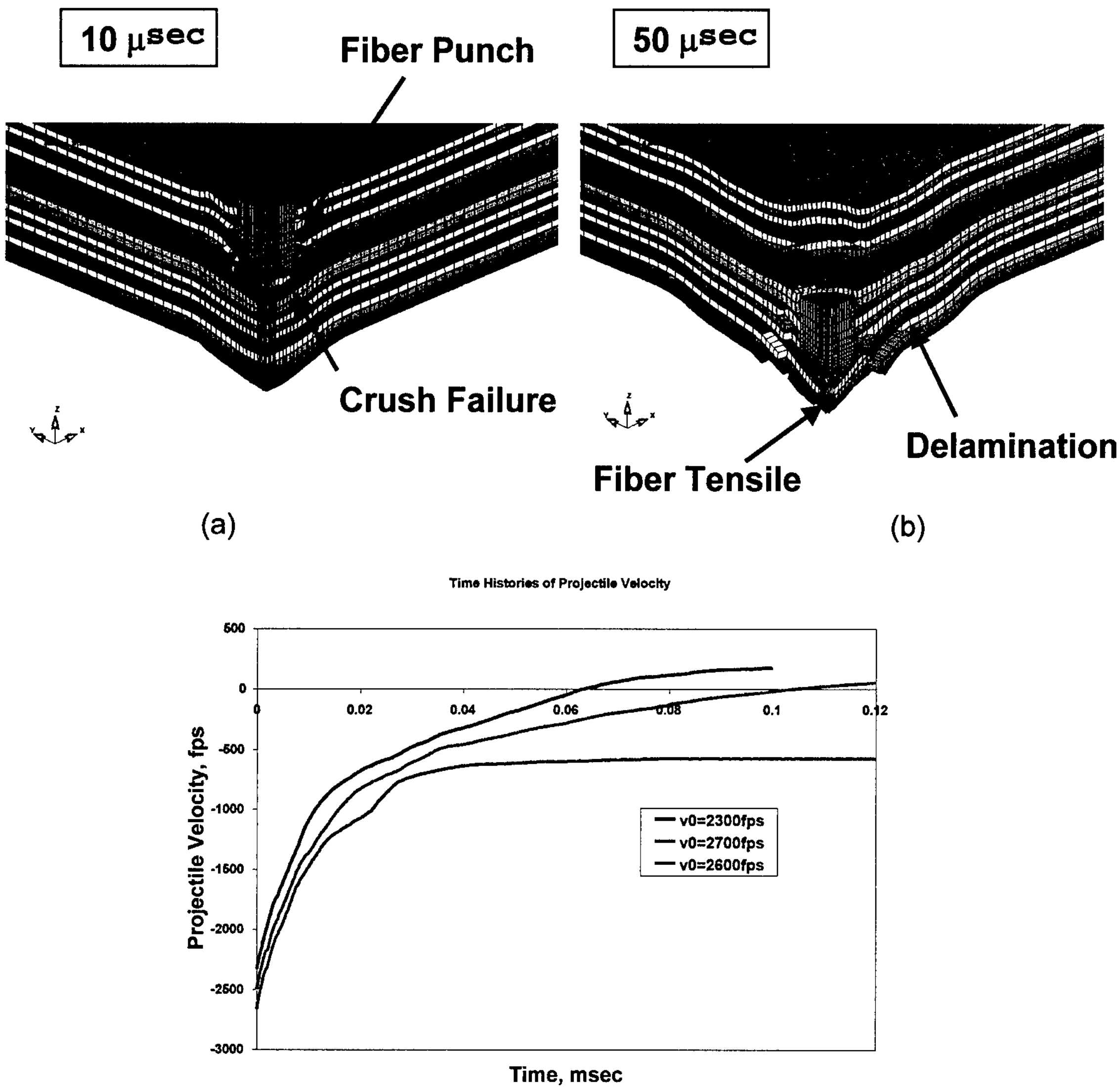
The LS-DYNA finite element code using the integrated progressive failure models has been utilized to evaluate the ballistic performance of various 2D and 3D woven composites of S2-Glass/Epoxy material. The selected woven constructions include: (1) plain weave laminate, (2) triaxial weave laminate, (3) 3D orthogonal weave, (4) 3D 4-step braided weave, and (5) 3D triaxial weave. A composite panel of 6"x6"x0.5" was considered. Analyses were performed to predict the perforation limit velocity (V50) of the composite panel subjected to a 0.22 caliber fragment simulation projectile (FSP) impact. The analyzed 2D and 3D woven composites are listed in Table 1. Note that it is important to identify repeating patterns in the geometry of the textile so that analysis can be performed to predict the material behavior. These repeating patterns are referred as unit cells and were used to construct the representative volume for the minimechanics model. The unit cell models for 3D braids were obtained from literature, e.g. [2]. The unit cell models for those 3D triaxial weaves are identified Figure 2. According to the fiber architectures of individual composites, the associated representative unidirectional yarn bundles have been identified and are listed in Table 1.

Figure 3 shows the results of ballistic analysis of a composite plate of a plain laminate. The S2-GLASS/SC-15 fabric composite armor panel with an areal weight of 5 psf was subjected to a 0.22 calibre FSP impact. Figures 3a and 3b show the deformed mesh at 10 micro-sec and 30 micro-sec, respectively. The failure modes are: (1) fiber shear punch and fiber crush failure initiated from the top of plate due to the direct contact of the FSP, and (2) fiber tensile failure initiated from the bottom of the plate. Figure 3c shows the time histories of projectile velocity for three values of initial. Note that the initial velocity is negative (downward) and the rebounding velocity is positive (upward). It demonstrates that the progressive damage model implemented in this study provide a prediction of V50 of 2600 fps.

Table 1. Representative Bundles Used to Model the Selected 2D and 3D Woven Composites

Composite	Number of Rep. Bundles	Bundle Volume Fraction	Bundle Direction Cosines (x,y,z)
Plain Weave Laminate	2	(0. 5,0.5)	(1,0,0) (0,1,0)
Triaxial Weave Laminate	3	(0.334,0.333,0.333)	(1,0,0) (0.5,0.866,0) (-0.5,0.866,0)
3D Orthogonal Weave	3	(0.42,0.42,0.16)	(1,0,0) (0,1,0) (0,0,1)
3D Triaxial Weave	5	(0.28,0.28,0.28,0.08,0.08)	(1,0,0) (0.5,0.866,0) (-0.5,0.866,0) (0.866,0.0,0.5) (-0.866,0.0,0.5)
4-Step Braid	4	(0.25,0.25,0.25,0.25)	(0.626,0.433,0.649) (0.626,-0.433,0.649) (0.626,0.433,-0.649) (0.626,-0.433,-0.649)

The predicted V50 values for the analyzed composites are compared in Figure 4. It shows that both plain weave and triaxial weave laminates provide nearly the same V50 for the panel consisting of 50% fiber volume fraction subjected to high velocity 0.22 FSP impact. With the addition of through the thickness reinforcing yarns, the reduced bundle volume fractions of the in-plane yarns (for fixed fiber volume fraction) results in slight reduction V50 for both the 3D biaxial orthogonal and triaxial weaves, while the triaxial weave is about 5% higher than the orthogonal weave. Both of the triaxial designs provide 16% higher V50 than the 4-step braided composite. It should be noted that the conclusion is only limited to the high speed hard FSP projectile. It is expected that the results will likely be effected by the projectile type such as blunt projectiles.



(c)

Figure 3. MSC material models integrated into LS-DYNA allow simulation of progressive failure and prediction of experimental V50 of 1750 fps for a composite armor panel subjected to 0.50 calibre FSP ballistic impact, (a) deformed mesh plot at 10 micro-sec, (b) deformed mesh plot at 30 micro-sec, (c) cross-section of damaged specimen, and (d) time histories of projectile velocity

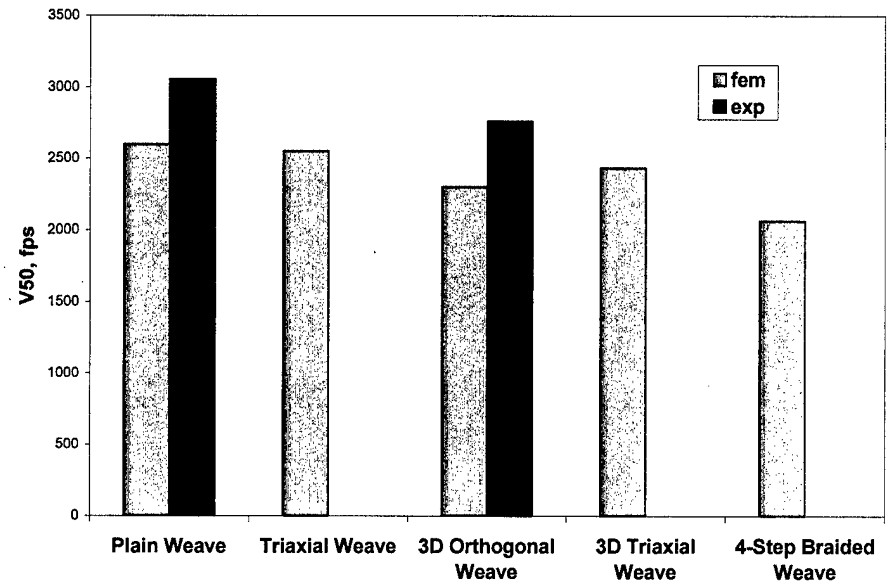


Figure 4. Comparison of predicted and test values of V50 for various selected 2D and 3D composite systems

TASK III. TESTING COUPON FABRICATION

Fabrication of 3D Woven Composites and Test Panels

The 3D triaxial constructions (Figure 2) as well as the close interweaving 3D orthogonal weave (Figure 1) has been provided to STFPS-CU. A study was made to determine the feasibility of weaving triaxial fabrics for the reinforcement of composites such that through the thickness running yarns are provided in addition to the in-plane triaxial constructions.

STFPS-CU has fabricated the 3D orthogonal weave preform and will utilize their newly acquired loom to fabricate the MSC designed 3D triaxial fiber architectures.

Utilizing the preforms of S2 Glass, eight plain weave and four 3D biaxial orthogonal weave panels were manufactured by a single step vacuum-assisted resin transfer molding (VARTM) process with SC-15 epoxy. The panels were post cured and ready for ballistic testing. Dimensions of all the targets are nominally 6"x6"x0.5" in thickness.

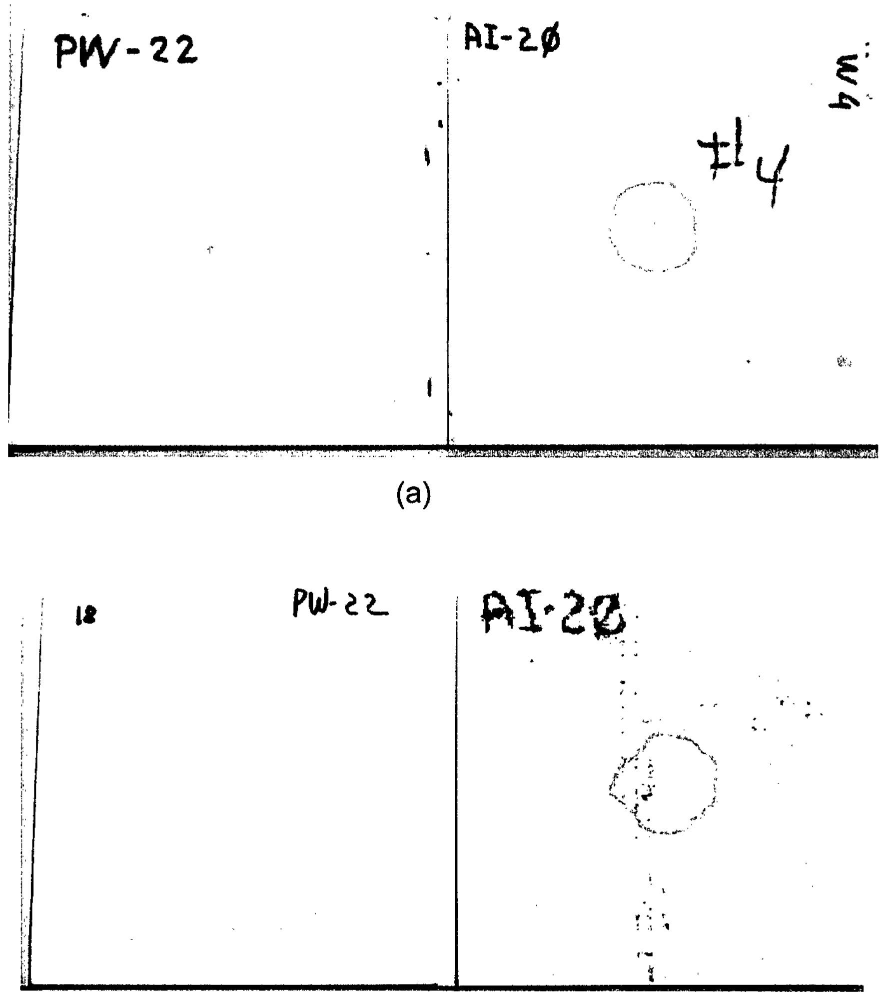
TASK IV. BALLISTIC TESTING AND CORRELATION

Ballistic tests of the composite armor panels were conducted at the testing facility of H.P. White. Each ballistic target was clamped at each of the four corners to a steel mounting frame. Ballistic tests were accomplished with each panel subjected to a single shot at the center location by a 0.22 caliber FSP projectile. A series of eight coupons of plain weave, which had an average area weight of 4.55 psf, were tested to determine the V-50 value of 2780 fps. The four orthogonal weave panels, which had the average area weight of 5.19 psf, were tested to obtain the V-50 of 2869 psf. Two impacted panels for the plain weave and the orthogonal weave for which the FSP completely penetrated the panels are shown in Figure 5. The ballistic damage on the surface of the panels is visually inspected. Surface layer delamination is visible on both sides of both panels. It is seen that the delamination of back surface in the orthogonal weave panels is much smaller than that of the plain weave panel. This demonstrates that the panel delamination is significantly reduced by the through the thickness interweaving yarn in the orthogonal panels. It is expected the post impact compressive residual strength of orthogonal weave will be much higher than that of the plain weave.

Figure 4 shows the V50 of analyzed composites as well as the experimental data, which are normalized to an area weight of 5.0 psf for the two impacted material systems. It is seen that the tested values are under predicted by the LS-DYNA analyses by less than 18%, which is reasonable considering the uncertainty on the rate dependent material properties. Further refinement and correlation of the progressive failure model for 3D woven composites will be performed in the Phase II study.

PLAN

Parametric studies (Task II) and specimen fabrication (Task III) will be completed in the next reporting period. Ballistic tests will be performed on additional series of armor panels.



(a)

(b)

Figure 5. Face Visual Damage of Impacted Panels (Plain Wave on the Left and Orthogonal Weave on the Right) (a) Front Face, and (b) Back Face

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